

2014-03-16

Seismic anisotropy of the Archean crust in the Minnesota River Valley, Superior Province

Ferre, EC

<http://hdl.handle.net/10026.1/14975>

10.1002/2013GL059116

Geophysical Research Letters

All content in PEARL is protected by copyright law. Author manuscripts are made available in accordance with publisher policies. Please cite only the published version using the details provided on the item record or document. In the absence of an open licence (e.g. Creative Commons), permissions for further reuse of content should be sought from the publisher or author.



RESEARCH LETTER

10.1002/2013GL059116

Key Points:

- The Archean crust of the Minnesota River Valley is strongly anisotropic
- The horizontally layered crust of the MRV cannot split vertical shear waves
- The cause of low SWS in the MRV must be in the uppermost mantle

Supporting Information:

- Readme
- Figure S1
- Tables S1–S3

Correspondence to:

E. C. Ferré,
eferre@geo.siu.edu

Citation:

Ferré, E. C., A. Gëbelin, J. A. Conder, N. Christensen, J. D. Wood, and C. Teyssier (2014), Seismic anisotropy of the Archean crust in the Minnesota River Valley, Superior Province, *Geophys. Res. Lett.*, 41, 1514–1522, doi:10.1002/2013GL059116.

Received 23 DEC 2013

Accepted 13 FEB 2014

Accepted article online 17 FEB 2014

Published online 11 MAR 2014

Corrected 4 NOV 2014

This article was corrected on 4 NOV 2014.
See the end of the full text for details.

Seismic anisotropy of the Archean crust in the Minnesota River Valley, Superior Province

Eric C. Ferré¹, Aude Gëbelin², James A. Conder¹, Nik Christensen³, Justin D. Wood¹, and Christian Teyssier⁴
¹Department of Geology, Southern Illinois University, Carbondale, Illinois, USA, ²Biodiversity and Climate Research Center (BiK-F), Frankfurt/Main, Germany, ³Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia, Vancouver, British Columbia, Canada, ⁴Department of Earth Sciences, University of Minnesota Twin Cities, Minneapolis, Minnesota, USA

Abstract The Minnesota River Valley (MRV) subprovince is a well-exposed example of late Archean lithosphere. Its high-grade gneisses display a subhorizontal layering, most likely extending down to the crust-mantle boundary. The strong linear fabric of the gneisses results from high-temperature plastic flow during collage-related contraction. Seismic anisotropies measured up to 1 GPa in the laboratory, and seismic anisotropies calculated through forward-modeling indicate $\Delta V_p \sim 5\text{--}6\%$ and $\Delta V_s \sim 3\%$. The MRV crust exhibits a strong macroscopic layering and foliation, and relatively strong seismic anisotropies at the hand specimen scale. Yet the horizontal attitude of these structures precludes any substantial contribution of the MRV crust to shear wave splitting for vertically propagating shear waves such as SKS. The origin of the regionally low seismic anisotropy must lie in the upper mantle. A horizontally layered mantle underneath the United States interior could provide an explanation for the observed low SWS.

1. Introduction

Seismic anisotropy in continental areas originates primarily from lattice preferred orientation (LPO) in the mantle and the crust [e.g., Karato, 1987; Nicolas and Christensen, 1987; Mainprice and Silver, 1993]. Seismic anisotropy has received considerable attention because it informs both active motion and ancient deformation of lithosphere/asthenosphere on a scale that is only matched by active displacement fields of active tectonic regions from geodetic data (Global Positioning System). However, the timing and specific mechanisms resulting in LPO in the continental crust remain far less understood than that in the oceanic lithosphere. [e.g., Fountain and Christensen, 1989; Kern, 1990; Silver and Chan, 1991; Barruol and Mainprice, 1993; Silver, 1996; Savage, 1999; Eaton and Jones, 2006].

Seismic anisotropy in the upper mantle arises primarily from olivine and pyroxene LPO acquired through plastic flow [Hess, 1964; Peselnik et al., 1974; Fuchs, 1977; Christensen, 1984; Karato, 1987; Nicolas and Christensen, 1987; Mainprice and Silver, 1993]. In contrast, the origin of crustal seismic anisotropy is more elusive [Mainprice and Nicolas, 1989; Ozacar and Zandt, 2004; Shapiro et al., 2004; Christensen and Mooney, 1995; Barruol and Kern, 1996; Fouch and Rondenay, 2006]. Crustal seismic anisotropy may be related to minerals LPO, like in the mantle, or with metamorphic layering, aligned cracks, or some combination of these structures.

Within continental areas, some cratonic domains display large seismic anisotropies and hence constitute legitimate targets to investigate the origin and significance of anisotropy. Archean provinces such as the Superior Province, the Sao Francisco Craton, or the Kaapvaal Craton show some of the largest splitting delay times, $\delta t \approx 1.5$ s, observed on continents [e.g., Vinnik et al., 1995; James and Assumpção, 1996; Barruol et al., 1997]. These provinces also exhibit large internal variability in the fast seismic directions [e.g., Waite et al., 2005]. Together with their correlation with the orientation of surface tectonic features, these variations suggest that crustal domains were assembled by the amalgamation of microplates [e.g., De Wit et al., 1992].

The most routinely determined measure of seismic anisotropy is from shear wave splitting. Splitting of teleseismic shear waves such as SKS waves results from integration of anisotropy from the core-mantle boundary to the Earth's surface. Because the mantle portion of the raypath is much longer than the crustal portion, researchers often discount the crust as a major contributor to shear wave splitting observations.

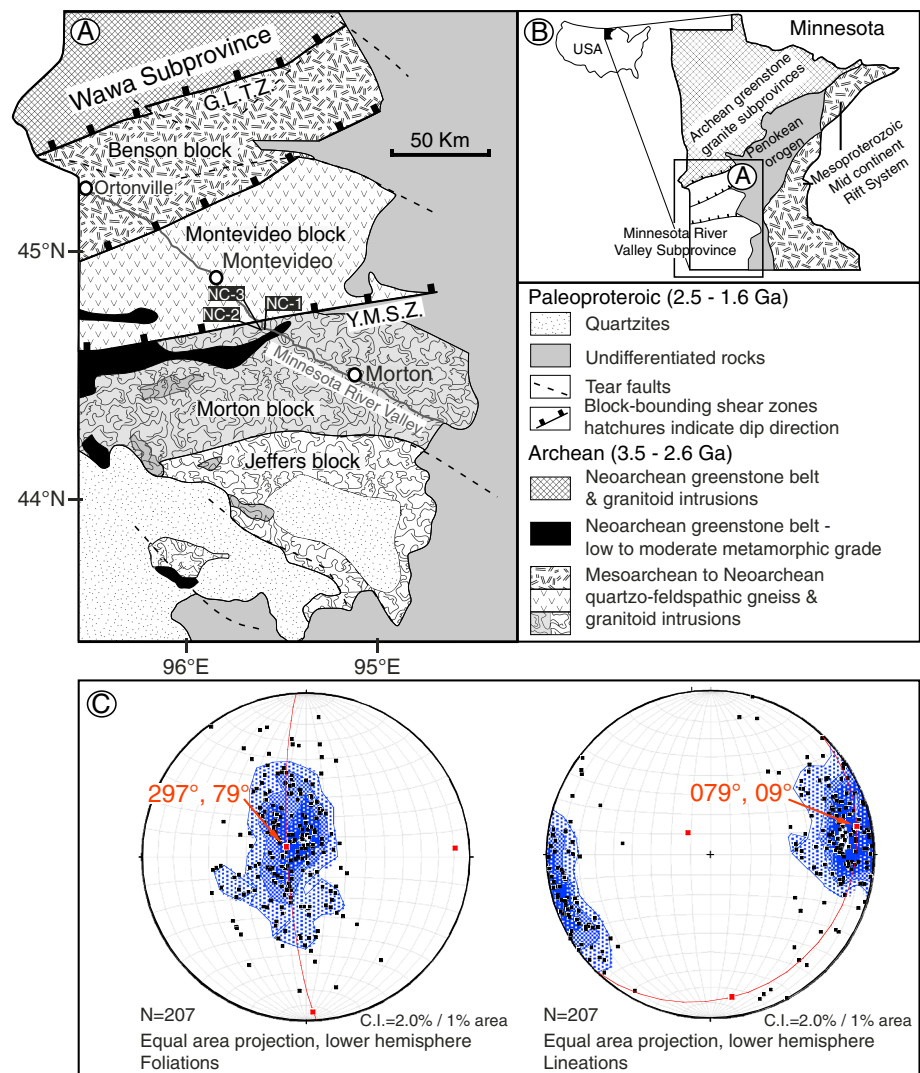


Figure 1. (a) Simplified bedrock geological map of the Minnesota River Valley (MRV) subprovince, showing major crustal-scale shear zones [Schmitz *et al.*, 2006]. (b) Box outline of Figure 1a. (c) Stereonets, lower hemisphere, equal area projection of anisotropy of magnetic susceptibility for Morton gneisses [Ferré *et al.*, 2003].

While much of the Superior Province exhibits splitting times greater than 1 s [Barruol *et al.*, 1997; Gao *et al.*, 1997; Frederiksen *et al.*, 2007, 2013], surprisingly, splitting times in the Minnesota River Valley (MRV) are closer to a few tenths of a second [Frederiksen *et al.*, 2013]. Total splitting times of a few tenths of a second require a careful accounting of crustal anisotropy for reliable interpretation.

Here, we investigate the origin and tectonic significance of seismic anisotropy in the Archean lower crustal rocks exposed in the MRV. We combine direct laboratory measurements, petrofabric analysis, and forward modeling of rock elastic properties that can be translated in terms of anisotropy of teleseismic shear wave propagation. The measured and predicted seismic anisotropies are then used to quantify the respective contributions of the crust and upper mantle to splitting delay times.

2. Tectonic Setting of the Minnesota River Valley Complex, Superior Province

The Superior Province, an Archean craton, forms the core of the North American continent [e.g., Hoffman, 1989; Card, 1990; Darbyshire *et al.*, 2007]. This province consists of terranes amalgamated along WSW-ENE trending shear zones (Figure 1). The Minnesota River Valley constitutes one of the best exposed sections of late Archean continental lithosphere in the Superior Province. It consists primarily of high-grade, coarse-grained,

and layered gneisses metamorphosed in the upper amphibolite to granulite facies. This metamorphic package of Archean rocks forms the autochthon of Proterozoic units to the North. Across the four tectonic blocks of the MRV, gneissic rocks consistently display a subhorizontal layering and a subhorizontal foliation. COCORP seismic reflection profiles suggest that this persistent broadly horizontal tectonic fabric most likely extends down to the crust-mantle boundary to a depth of 45–51 km [Gibbs *et al.*, 1984]. The MRV Complex constitutes the southernmost subprovince of the Superior Province [e.g., Southwick and Chandler, 1996]. To the north, the shallowly north dipping Great Lakes Tectonic Zone (GLTZ) separates the MRV from the Wawa Subprovince [Figure 1, Gibbs *et al.*, 1984; Southwick and Chandler, 1996]. The MRV subprovince shows a layered crust-mantle transition at 45–51 km depth [Gohl *et al.*, 1993], possibly corresponding to a “magmatic underplating” type of Moho [Eaton, 2006]. The thickness of the crust is slightly above the average for Archean crusts and also appears consistent with basaltic underplating [Durrheim and Mooney, 1991]. The average crustal P wave velocity ranges from 6.5 to 7.0 km/s, while the base of the crust shows higher velocities that range from 6.8 to 7.5 km/s [Southwick and Chandler, 1996]. Seismic refraction surveys indicate rapid variations in thickness, at the scale of a few km across the tectonic grain [Braile, 1989]. The MRV consists of four juxtaposed Archean crustal blocks, the Benson, Montevideo, Morton, and Jeffers blocks from north to south (Figure 1). Abundant and fresh exposures along the MRV consist of quarries and glacier-polished outcrops, while Late Cretaceous sedimentary rocks and Quaternary glacial deposits cover the rest. While exposures are limited to the river valley, potential field geophysics provides a three-dimensional view of these rocks [Southwick and Chandler, 1996].

The four blocks of the MRV host broadly similar rock types, mainly quartzo-feldspathic migmatites with minor tonalitic, granodioritic, dioritic, and pelitic layers that grade into each other. The northernmost Benson block hosts more plutonic material than the other three blocks to the south, including tonalites, quartz diorites, and granodiorites with well-preserved igneous microstructures. The Montevideo and Morton blocks preserve Mesoproterozoic crustal segments that were deformed and metamorphosed during Neoproterozoic accretion of the MRV subprovince to the southern Superior Province. The migmatitic gneisses of the Morton block appear slightly more leucocratic than the rocks of the other blocks. These gneisses host amphibolite horizons interpreted as boudinaged tholeiitic basalt sills [Nielsen and Weiblen, 1980]. These four blocks differ in their geophysical properties [Southwick and Chandler, 1996], such as average rock density (Benson: $\rho = 2750 \text{ kg/m}^3$; Montevideo: $\rho = 2860 \text{ kg/m}^3$; Morton: $\rho = 2760 \text{ kg/m}^3$; Jeffers: $\rho = 2750 \text{ kg/m}^3$) and aeromagnetic anomalies, with the southernmost Jeffers block showing larger aeromagnetic anomalies than the other three blocks. The post-tectonic intrusions emplaced throughout the high-grade gneisses of the MRV might correspond to the granite “blooms” interpreted by Percival and Pysklywec [2007] as a result from lithospheric keel inversion.

The metamorphic foliation throughout the MRV is subparallel to a centimeter-scale to millimeter-scale compositional layering and generally shows shallow dips ($<20^\circ$). Mineral lineations and stretching lineations in these high-grade gneisses are scarce and parallel to gently plunging fold axes [Bauer, 1974, 1980]. The anisotropy of magnetic susceptibility (AMS) of the Morton migmatite records a high-temperature plastic fabric characterized by a subhorizontal foliation and a $N080^\circ$ trending subhorizontal lineation [Figure 1c; Ferré *et al.*, 2003, 2004]. The four blocks of the MRV are separated by WSW-ENE linear gravity and magnetic anomalies, some of which, like the Yellow Medicine Shear Zone (YMSZ), are regional north dipping shear zones (Figure 1). The YMSZ, separating the Montevideo and Morton blocks, was reactivated during the Penokean orogeny 2.45–1.75 Ga [Goldich and Wooden, 1980a, 1980b; Southwick and Chandler, 1996]. Historic seismicity is preferentially localized along block boundaries, which suggests that they may underline major lithospheric discontinuities [Mooney and Morey, 1981; Chandler, 1994].

Amphibolite- to granulite-facies assemblages have been reported by Himmelberg and Phinney [1967] and Goldich *et al.* [1980a, 1980b]. Goldich *et al.* established the Archean age of the MRV basement [Goldich *et al.*, 1970, 1980a, 1980b; Goldich and Hedge, 1974; Goldich and Wooden, 1980a, 1980b]. Recent ion microprobe (SHRIMP) and ID-TIMS U-Pb zircon data have further constrained the 3.42 to 3.52 Ga protolith ages of tonalitic to granitic gneisses in the Morton and Montevideo blocks [Bickford *et al.*, 2006; Schmitz *et al.*, 2006]. Both blocks subsequently experienced igneous and metamorphic overprints at ca. 3.38, 3.14, and 2.60 Ga. The timing of accretion of the MRV terranes to the southern Superior province was constrained by Schmitz *et al.* [2006], who used high-precision U-Pb monazite and zircon ages to date granulite-facies metamorphism at ~ 2.6 Ga. This metamorphism coincides with voluminous late- to post-kinematic granitoid intrusion, which those authors tentatively related to crustal melting resulting from collisional thickening of colliding MRV crust.

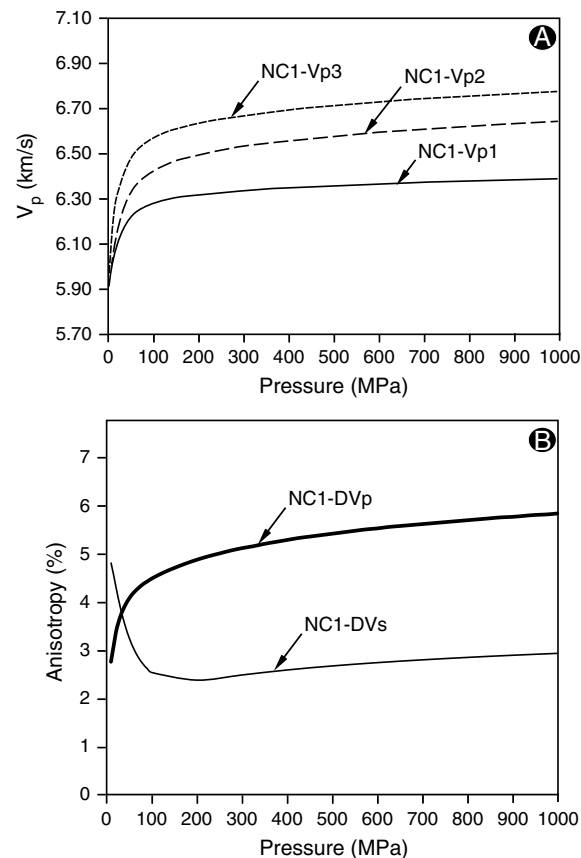


Figure 2. (a) P wave seismic velocity (km/s) as a function of confining pressure (MPa) measured in the laboratory for sample NC1 along three mutually perpendicular directions. (b) Seismic wave anisotropy measured in the laboratory on sample NC1 as a function of confining pressure up to 1 GPa. ΔV_p (bold line) shows an initial fast increase in anisotropy caused by crack closure, followed by a steady, near linear increase as a function of pressure, up to 5.8% at 1 GPa. ΔV_s (normal line) displays an initial decrease in anisotropy up to 150 MPa, followed by a steady increase up to 2.8% at 1 GPa.

of the Morton block [$\rho = 2760 \text{ kg/m}^3$; Chandler and Lively, 2003]. These results also indicate that up to a depth of approximately 7 km, corresponding to 200 MPa, the MRV rocks are likely to display a V_p anisotropy partially controlled by cracks and fractures. Below 7 km, the main contribution to crustal anisotropy would result primarily from rock fabric.

Compressional (V_p) and shear (V_s) wave velocities at hydrostatic pressures up to 1 GPa (equivalent to approximately 35 km depth) are reported as supporting information for three representative samples of Archean gneisses collected from the Morton block (locations shown in Figure 1). For each sample, compressional wave velocities were measured for three cores taken in mutually perpendicular directions, one normal to the layering ($144^\circ \text{ NE } 15^\circ$) and two in the plane of the layering, one of these being parallel to the mineral lineation ($070^\circ, 15^\circ$). V_p in supporting information is given for all the three measurements, and the average is shown in Figure 2a. Two shear wave velocities were measured for propagation in the layering planes and parallel to the sample lineations. V_{s1} is the fast shear wave vibrating parallel to the layering, and V_{s2} is the slow shear wave vibrating normal to the layering. For most rocks, this birefringence is a measure of maximum shear wave splitting (Figure 2b). The measured anisotropies take into account the orientations of several hundred thousand grains [Christensen, 1985] and the elongated and platy grain shapes of hornblende and biotite, which are the minerals primarily responsible for the anisotropies. At pressures below 200 MPa, oriented grain boundary cracks affect the anisotropies.

3. Laboratory Velocity Measurements

We performed measurements in the petrophysics laboratory at the University of British Columbia, following the procedure of Christensen [1971]. Samples were trimmed and polished to right circular cylinders with flat, parallel ends. Sample densities were determined from the volumes and weights of the rock cores. Velocities from single cores were measured as a function of confining pressure using the pulse transmission technique [Birch, 1960; Christensen, 1985]. First break picks for acquired waveforms are automatically selected by a computer interfaced with the pressure system. The estimated error in the velocities is 0.5%.

The mineral percentages given in the supporting information were obtained by point counting 1000 grains from each sample. These counts are from a single thin section and thus may not adequately represent the banded specimens. Sample NC1 is a quartzo-feldspathic biotite gneiss, and sample NC3 is a hornblende plagioclase gneiss, both with amphibolite-facies mineralogies. NC2 is a mafic granulite facies gneiss.

For NC-1, NC-2, and NC-3, we obtained average densities of $\rho = 2756, 3074$, and 2982 kg/m^3 , respectively; compressional wave seismic velocities of $V_p = 6.556, 6.843$, and 6.695 km/s at 550 MPa, a pressure equivalent to a depth of 20 km; and average seismic anisotropies of $\Delta V_p = 5.47, 4.31$, and 2.35% (with $\Delta V_p = 100(V(90^\circ) - V(0^\circ)) / 1/2(V(90^\circ) + V(0^\circ))$). We consider NC-1 the most representative sample for the Morton block because its measured density $\rho = 2756 \text{ kg/m}^3$ is near the average density

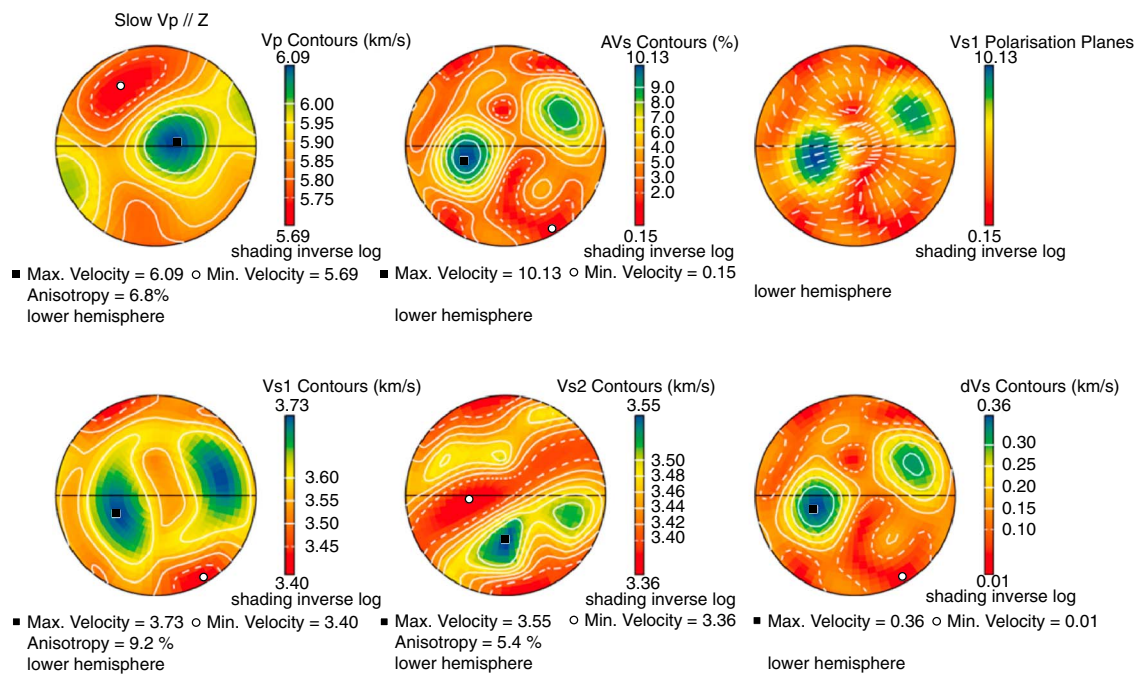


Figure 3. Forward modeling of seismic properties calculated for a biotite gneiss (212C) from LPO and mineral elastic constants. V_{PX} , V_{PY} , and V_{PZ} are the compressional wave velocities measured in the specimen finite strain reference framework where X is the lineation and Z is the pole to foliation.

The importance of the shear measurements is twofold. The measurements clearly demonstrate that the rocks produce splitting and more importantly give us an estimate of the maximum splitting for each sample. Previous studies of similar rocks at hydrostatic pressures to 1000 MPa [e.g., Christensen, 1966; Godfrey *et al.*, 2000], triaxial compression to 600 MPa [e.g., Kern *et al.*, 1997], and calculations using measured lattice preferred orientations of crustal minerals and their elastic properties at atmospheric pressure [Barruol and Mainprice, 1993] have shown that the magnitude of shear wave splitting decreases to almost zero as the propagation direction varies from the plane of the layering to the layering normal. Thus, for vertical propagation in the crust, steeply dipping layering will produce maximum splitting, and horizontal layering will result in minimum splitting. Calculated maximum splitting times for a 10 km crustal section with vertical layering, using velocities at mid-crustal pressures, are 0.07, 0.08, and 0.05 s for NC-1, NC-2, and NC-3. Variations of the layering from vertical will produce significantly lower split times.

4. Forward Modeling of Seismic Properties Based on Lattice Preferred Orientation (LPO)

We used the elastic properties of constituting mineral phases together with their LPOs determined by electron backscatter diffraction to calculate the directional seismic properties of two representative oriented gneisses. Details of this forward modeling method are described in Mainprice [1990] and Mainprice and Humbert [1994]. Modal compositions were determined by point counting on the same thin sections used for LPO measurements. We use published elastic data for quartz [McSkimin *et al.*, 1965; Calderon *et al.*, 2007; Lakshmanan *et al.*, 2007], alkali feldspar [Brown *et al.*, 2006], plagioclase [Carpenter, 2006], biotite [Simmons and Wang, 1971], and hornblende [Aleksandrov and Ryzhova, 1961; Bass, 1995; Isaak, 2001; Ji *et al.*, 2002].

Biotite-gneiss 212C consists of plagioclase [An_{24}] (61.4%), quartz (28.2%), and biotite (10.3%). The maximum anisotropy for P waves is 6.8%, with $V_{PY} > V_{PX} > V_{PZ}$ (Figure 3). Shear wave splitting (SWS) is highest in the foliation plane, a typical feature of biotite-dominated seismic properties, with the fastest polarization in the foliation plane. Hornblende-gneiss 212G consists of plagioclase [An_{24}] (71.4%), quartz (11.8%), and hornblende (17.0%). The maximum anisotropy for P waves is 5.4%, with $V_{PZ} > V_{PY} > V_{PX}$. SWS is complex, a typical feature of plagioclase-dominated seismic properties.

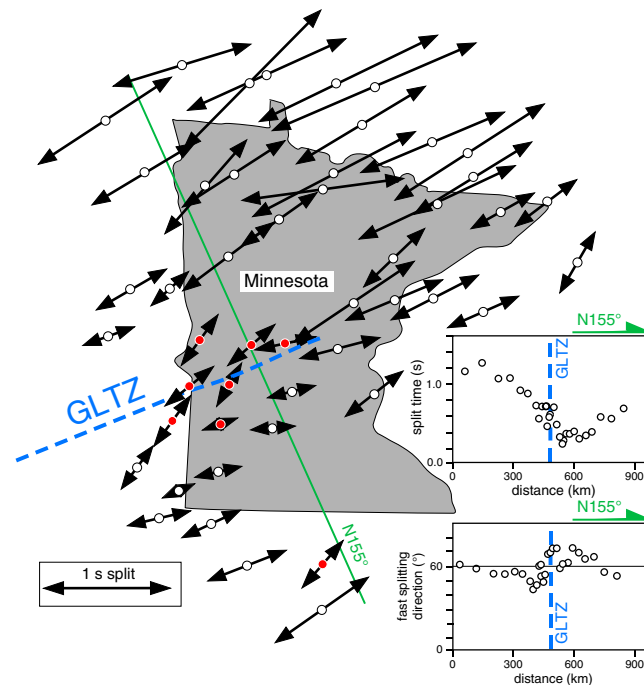


Figure 4. Summary of shear wave splitting (SWS) results for Minnesota and surrounding regions. New data (with red dots) merged with Frederiksen *et al.* [2013]'s SWS data. The Great Lakes Tectonic Zone (GLTZ) constitutes a lithospheric block boundary across which seismic anisotropy decreases rapidly from north to south. The splitting directions differ on either side of the GLTZ.

it seems likely that the same deformation process would also control the development of crustal anisotropy at a larger scale. To test this hypothesis, in the following, we investigate teleseismic anisotropy.

5. Shear Wave Splitting in the Minnesota River Valley

To more fully examine the seismic anisotropy across the MRV, we augment the results of Frederiksen *et al.* [2013] with SWS measurements of SKS waves using SplitLab [Wüstefeld *et al.*, 2008] for several USArray stations in the MRV. Our results, shown with red dots in Figure 4, are consistent with Frederiksen *et al.* [2013] in that we see a noticeable drop in splitting time as well as significant changes in fast direction over short distances in the MRV relative to surrounding craton. South and north of the MRV, splitting times tend to be >1 s and exhibit fast direction \sim N050°–060°, parallel to the absolute plate motion direction [Frederiksen *et al.*, 2007]. In the MRV, splitting times are typically <0.5 s and indicate an anomaly in splitting directions around the GLTZ (Figure 4). V_2 anisotropy for the Morton block hornblende gneiss would be almost nul for a vertically travelling S wave in a horizontally layered medium, as shown by previous studies elsewhere [e.g., Godfrey *et al.*, 2000].

6. Discussion and Conclusions

At the outcrop scale, the MRV Archean gneisses display a strong nearly horizontal macroscopic and magnetic planar fabric [Bauer, 1974; Ferré *et al.*, 2003, 2004]. The same rocks also exhibit a consistent macroscopic and magnetic linear fabric (Figure 1), interpreted as resulting from high-temperature plastic flow. The AMS recorded in the MRV high-grade gneisses preserves information on high-temperature deformation despite significant post-kinematic annealing, as described in granitic rocks elsewhere [Ferré and Améglio, 2000]. These linear fabrics, parallel to the MRV N075° block boundaries, most likely originate from collage-related tectonics during the MRV subprovince late-Archean assembly. The MRV terrane, with its gently north-dipping block boundaries, subsequently reactivated as transcurrent shear zones like the Yellow Medicine shear zone,

These results indicate that, in rocks dominated by plagioclase such as the gneisses of the MRV where plagioclase accounts for 40 to 80% in volume [Goldich *et al.*, 1980a, 1980b], small variations in Plag-Bt-Hbl volume fractions control the seismic properties. These results also show that $\approx 10\%$ of biotite, or $\approx 70\%$ of plagioclase or $\approx 20\%$ of hornblende would be capable of controlling bulk rock seismic properties. Overall, the seismic properties of mid- to lower crustal rocks depend primarily on the percentage of elastically anisotropic phases such as biotite or hornblende and to a lesser degree on the percentage of quartz and feldspars in the granulite- and amphibolite-facies Archean crust.

In the Morton block, the average magnetic lineation (N079°, 09°) and the forward modeled seismic anisotropy (N070°, 20°) have broadly similar azimuth. Since the magnetic fabrics in the MRV originated from high-temperature plastic flow during regional deformation [Ferré *et al.*, 2003],

shares striking similarities with the Limpopo Belt separating the Kaapvaal craton from the Zimbabwe craton [e.g., Silver *et al.*, 2004].

The MRV crust exhibits a strong macroscopic fabric, represented by compositional layering and foliation, and relatively strong seismic anisotropies at the hand specimen scale. Yet despite these significant anisotropies, the horizontal attitude of these structures precludes any substantial contribution of the MRV Archean crust to SWS. The origin of the regionally low seismic anisotropy must therefore lie in the mantle, although it is emphasized that the crust is significantly anisotropic and will produce strong shear wave splitting for horizontal wave propagation. The total crustal delay time has been estimated to be 0.1 s in other regions using Moho-converted PmS phases [McNamara and Owens, 1993]. The vertical tectonics hypothesis proposed by Frederiksen *et al.* [2013] is not supported by any structures in the field. One would expect diapiric tectonics to be expressed in map patterns similar to those of the Chindamora Batholith of Zimbabwe [e.g., Ramsay, 1975], and this is not the case [Southwick, 2002].

The concept of a horizontally layered mantle underneath the United States interior [Yuan and Romanowicz, 2010] could provide an explanation for the observed low SWS if two superimposed mantle layers contributed destructively to seismic anisotropy.

Acknowledgments

The Gibson Fund of the University of Minnesota, Rhodes University, and the South African Foundation for Research Development are kindly acknowledged for support of E. Ferré's sabbatical leave in 2000. The University of Minnesota provided additional funding to Aude Gébelin. We thank Cold Springs Granite and Chuck Mulhbauser for providing access to the Morton quarries. The velocity measurements were supported by NSF grant EAR-1010645. We are indebted to Paul Morin, for processing the digital images using *Iris Explorer*, and David Mainprice, for the forward modeling using *Aniso2K*. Philip Fortin is gratefully acknowledged for his logistical assistance. The editor, Michael Wyssession, and an anonymous reviewer are sincerely acknowledged for helping us strengthen this manuscript.

The Editor thanks an anonymous reviewer for his/her assistance in evaluating this manuscript.

References

- Aleksandrov, K. S., and T. V. Ryzhova (1961), The elastic properties of rock forming mineral: II. Layered silicates, *Bulletin Academia U.S.S.R., Geophys. Ser. Engl. Transl.*, 9, 1165–1168.
- Barruol, G., and D. Mainprice (1993), A quantitative evaluation of the contribution of crustal rocks to the shear-wave splitting of teleseismic SKS waves, *Phys. Earth Planet. Inter.*, 78(3–4), 281–300.
- Barruol, G., and H. Kern (1996), Seismic anisotropy and shear-wave splitting in lower-crustal and upper-mantle rocks from the Ivrea zone; experimental and calculated data, *Phys. Earth Planet. Inter.*, 95(3–4), 175–194.
- Barruol, G., P. G. Silver, and A. Vauchez (1997), Seismic anisotropy in the eastern United States: Deep structure of a complex continental plate, *J. Geophys. Res.*, 102(B4), 8329–8348.
- Bass, J. D. (1995), Elastic properties of minerals, melts, and glasses, in *Handbook of Physical Constants*, edited by T. J. Ahrens, pp. 45–63, AGU, Washington D. C.
- Bauer, R. L. (1974), Gneisses at Granite Falls and Montevideo, Minnesota, MSc thesis, 108 p., Univ. of Missouri-Columbia, Columbia, Mo.
- Bauer, R. L. (1980), Multiphase deformation in the Granite Falls - Montevideo area, Minnesota River Valley, in *Selected Studies of Archean gneisses and Lower Proterozoic Rocks in the Southern Canadian Shield*, edited by G. N. Hanson and G. B. Morey, pp. 1–17, Geol. Soc. Am., Special Paper, Boulder, Colo.
- Bickford, M. E., et al. (2006), SHRIMP study of zircons from Early Archean rocks in the Minnesota River Valley: Implications for the tectonic history of the Superior Province, *Geol. Soc. Am. Bull.*, 118(1–2), 94–108.
- Birch, F. (1960), The velocity of compressional waves in rocks to 10 kilobars - Part 1, *J. Geophys. Res.*, 65(4), 1083–1102.
- Braile, L. W. (1989), Crustal structure of the continental interior, in *Geophysical Framework of the Continental United States*, edited by L. C. Pakiser and W. D. Mooney, pp. 285–315, Geol. Soc. Am., Boulder, Colo.
- Brown, J. M., et al. (2006), Triclinic elastic constants for low albite, *Phys. Chem. Miner.*, 33(4), 256–265.
- Calderon, E., et al. (2007), Complete determination of the elastic moduli of alpha-quartz under hydrostatic pressure up to 1 GPa: An ultrasonic study, *J. Phys. Condens. Matter*, 19(43), 436,228.
- Card, K. D. (1990), A review of the Superior Province of the Canadian Shield, a product of Archean accretion, *Precambrian Res.*, 48, 99–156.
- Carpenter, M. A. (2006), Elastic properties of minerals and the influence of phase transitions, *Am. Mineral.*, 91(2–3), 229–246.
- Chandler, V. (1994), *Minnesota at a Glance. Earthquakes in Minnesota*, 4 pp., Univ. of Minnesota, Minneapolis, Minn.
- Chandler, V. W., and R. S. Lively (2003), Rock properties database: Density, magnetic susceptibility, and natural remanent magnetization of rocks in Minnesota, edited, Minnesota Geological Survey, St. Paul, Minnesota.
- Christensen, N. I. (1966), Shear wave velocities in metamorphic rocks at pressures to 10 kilobars, *J. Geophys. Res.*, 71, 3549–3556.
- Christensen, N. I. (1971), Fabric, seismic anisotropy, and tectonic history of the Twin Sisters dunite, Washington, *Geol. Soc. Am. Bull.*, 82, 1681–1694.
- Christensen, N. I. (1984), The magnitude, symmetry and origin of upper mantle anisotropy based on fabric analyses of ultramafic tectonites, *Geophys. J. R. Astron. Soc.*, 76, 89–111.
- Christensen, N. I. (1985), *Measurements of Dynamic Properties of Rock at Elevated Pressures and Temperatures*, edited by H. J. Pincus and E. R. Hoskins, pp. 93–107, American Society for Testing and Materials, Philadelphia, Pa.
- Christensen, N. I., and W. D. Mooney (1995), Seismic velocity structure and composition of the continental crust: A global view, *J. Geophys. Res.*, 100(B6), 9761–9788.
- Darbyshire, F. A., D. W. Eaton, A. W. Frederiksen, and L. Ertolahti (2007), New insights into the lithosphere beneath the Superior Province from Rayleigh wave dispersion and receiver function analysis, *Geophys. J. Int.*, 169(3), 1043–1068, doi:10.1111/j.1365-1246X.2006.03259.x.
- de Wit, M. J., et al. (1992), Formation of an Archaean continent, *Nature*, 357(6379), 553–562.
- Durrheim, R. J., and W. D. Mooney (1991), Archean and Proterozoic crustal evolution; evidence from crustal seismology, *Geology*, 19(6), 606–609.
- Eaton, D. W. (2006), Multi-genetic origin of the continental Moho: Insights from Lithoprobe, *Terra Nova*, 18, 34–43.
- Eaton, D. W., and A. G. Jones (2006), Tectonic fabric of the subcontinental lithosphere: Evidence from seismic, magnetotelluric and mechanical anisotropy, *Phys. Earth Planet. Inter.*, 158(2–4), 85–91.
- Ferré, E. C., and L. Améglio (2000), Preserved magnetic fabrics vs. annealed microstructures in the syntectonic recrystallised George granite, South Africa, *J. Struct. Geol.*, 22(8), 1199–1219.

- Ferré, E. C., C. Teyssier, M. Jackson, J. W. Thill, and E. S. G. Rainey (2003), Magnetic Susceptibility Anisotropy: A new petrofabric tool in migmatites, *J. Geophys. Res.*, *108*(B2), 2086, doi:10.1029/2002JB001790.
- Ferré, E. C., et al. (2004), Paramagnetic and ferromagnetic anisotropy of magnetic susceptibility in migmatites: Measurements in high and low fields and kinematic implications, *Geophys. J. Int.*, *157*(3), 1119–1129.
- Fouch, M. J., and S. Rondenay (2006), Seismic anisotropy beneath stable continental interiors, *Phys. Earth Planetary Inter.*, *158*(2–4), 292–320.
- Fountain, D. M., and N. I. Christensen (1989), Composition of the continental crust and upper mantle: A review, in *Geophysical Framework of the Continental United States*, edited by L. C. Pakiser and W. D. Mooney, pp. 711–742, Geol. Soc. Am., Boulder, Colo.
- Frederiksen, A. W., S.-K. Miong, F. A. Darbyshire, D. W. Eaton, S. Rondenay, and S. Sol (2007), Lithospheric variations across the Superior Province, Ontario, Canada: Evidence from tomography and shear wave splitting, *J. Geophys. Res.*, *112*, B07318, doi:10.1029/2006JB004861.
- Frederiksen, A. W., I. Deniset, O. Ola, and D. Toni (2013), Lithospheric fabric variations in central North America: Influence of rifting and Archean tectonic styles, *Geophys. Res. Lett.*, *40*, 4583–4587, doi:10.1002/grl.50879.
- Fuchs, K. (1977), Seismic anisotropy of the subcrustal lithosphere as evidence for dynamical processes in the upper mantle, *Geophys. J. Roy. Astron. Soc.*, *49*, 167–179.
- Gao, S., P. M. Davis, H. Liu, P. D. Slack, A. W. Rigor, Y. A. Zorin, V. V. Mordvinova, V. M. Kozhevnikov, and N. A. Logatchev (1997), SKS splitting beneath continental rift zones, *J. Geophys. Res.*, *102*(B10), 22,781–22,797.
- Gibbs, A. K., et al. (1984), Seismic-reflection study of the Precambrian crust of central Minnesota, *Geol. Soc. Am. Bull.*, *95*(3), 280–294.
- Godfrey, N. J., N. I. Christensen, and D. A. Okaya (2000), Anisotropy of schists: Contribution of crustal anisotropy to active source seismic experiments and shear wave splitting observations, *J. Geophys. Res. Sol. Earth*, *105*(B12), 27,991–28,007.
- Gohl, K., R. B. Hawman, and S. B. Smithson (1993), Wide-angle reflection studies of the crust and Moho beneath the Archean gneiss terrane of Southern Minnesota, *Geophys. Res. Lett.*, *20*(7), 619–622.
- Goldich, S. S., and C. E. Hedge (1974), 3,800-Myr granitic gneiss in south-western Minnesota, *Nature*, *252*(5483), 467–468.
- Goldich, S. S., and J. L. Wooden (1980a), Origin of the Morton Gneiss, southwestern Minnesota: Part 3. Geochronology, *Geol. Soc. Am. Spec. Pap.*, *182*, 77–94.
- Goldich, S. S., and J. L. Wooden (1980b), Geochemistry of the Archean rocks in the Morton and Granite Falls areas, southwestern Minnesota, *Precambrian Res.*, *11*(3–4), 267–296.
- Goldich, S. S., et al. (1970), Age of the Morton and Montevideo gneisses and related rocks, southwestern Minnesota, *Geol. Soc. Am. Bull.*, *81*(12), 3671–3695.
- Goldich, S. S., et al. (1980a), Archean rocks of the Granite Falls area, southwestern Minnesota, in *Selected Studies of Archean gneisses and Lower Proterozoic Rocks, Southern Canadian Shield*, edited by G. B. Morey and G. N. Hanson, pp. 19–43, Geological Society of America, Boulder, Colo.
- Goldich, S. S., et al. (1980b), Origin of the Morton Gneiss, southwestern Minnesota: Part 1. Lithology, *Geol. Soc. Am. Spec. Pap.*, *182*, 45–56.
- Hess, H. H. (1964), Seismic anisotropy of the uppermost mantle under oceans, *Nature*, *203*, 629–631.
- Himmelberg, G. R., and W. C. Phinney (1967), Granulite-Facies Metamorphism, Granite Falls-Montevideo Area, Minnesota, *J. Petrol.*, *8*(3), 325–348.
- Hoffman, P. F. (1989), Precambrian geology and tectonic history of North America, in *The Geology of North America - An Overview*, edited by A. W. Bally and A. R. Palmer, pp. 447–512, Geol. Soc. Am., Boulder, Colo.
- Isaak, D. G. (2001), Elastic properties of minerals and planetary objects, in *Handbook of Elastic Properties of Solids, Liquids, and Gases*, Elastic Properties of Solids: Biological and Organic Materials, vol. III, edited by B. a. S. Levy, pp. 325–376, Academic Press, Waltham, Mass.
- James, D. E., and M. Assumpção (1996), Tectonic implications of S-wave anisotropy beneath SE Brazil, *Geophys. J. Int.*, *126*(1), 1–10.
- Ji, S., et al. (2002), *Handbook of Seismic Properties of Minerals, Rocks and Ores*, Polytechnic International Press, Montreal, Que.
- Karato, S. (1987), Seismic anisotropy due to lattice preferred orientation of minerals: Kinematic or dynamic, in *High-Pressure Research in Mineral Physics*, edited by M. H. Manghnani and Y. Syono, pp. 455–471, TERRAPUB AGU, Tokyo/Washington, D. C.
- Kern, H. (1990), Laboratory seismic measurements: An aid in the interpretation of seismic field data, *Terra Nova*, *2*(6), 617–628.
- Kern, H., B. Liu, and T. Popp (1997), Relationship between anisotropy of P and Swave velocities and anisotropy of attenuation in serpentinite and amphibolite, *J. Geophys. Res.*, *102*(B2), 3051–3065.
- Lakshatnov, D. L., et al. (2007), High-temperature phase transitions and elasticity of silica polymorphs, *Phys. Chem. Miner.*, *34*, 11–22.
- Mainprice, D. (1990), An efficient Fortran program to calculate seismic anisotropy from the lattice preferred orientation of minerals, *Comput. Geosci.*, *16*, 385–393.
- Mainprice, D., and A. Nicolas (1989), Development of shape and lattice preferred orientations; application to the seismic anisotropy of the lower crust, *J. Struct. Geol.*, *11*(1–2), 175–189.
- Mainprice, D., and M. Humbert (1994), Methods of calculating petrophysical properties from lattice preferred orientation data, *Surv. Geophys.*, *15*, 575–592.
- Mainprice, D., and P. Silver (1993), Interpretation of SKS-waves using samples from the subcontinental lithosphere, *Phys. Earth Planet. Inter.*, *78*, 257–280.
- McNamara, D. E., and T. J. Owens (1993), Azimuthal shear wave velocity anisotropy in the Basin and Range province using Moho Ps converted phases, *J. Geophys. Res.*, *98*, 12,003–12,017.
- McSkimin, H. J., et al. (1965), Elastic Moduli of Quartz versus Hydrostatic Pressure at 25C and -195.8C, *J. Appl. Phys.*, *36*(5), 1624–1632.
- Mooney, H. M., and G. B. Morey (1981), Seismic history of Minnesota and its geological significance, *Bull. Seismol. Soc. Am.*, *71*(1), 199–210.
- Nicolas, A., and N. I. Christensen (1987), Formation of anisotropy in upper mantle peridotites; a review, in *Composition, Structure and Dynamics of the Lithosphere-Asthenosphere System*, edited by K. Fuchs and C. Froidevaux, pp. 111–123, AGU, Washington, D. C.
- Nielsen, B. V., and P. W. Weiblen (1980), Mineral and rock compositions of mafic enclaves in the Morton Gneiss, *Geol. Soc. Am. Spec. Pap.*, *182*, 95–103.
- Ozacar, A. A., and G. Zandt (2004), Crustal seismic anisotropy in central Tibet: Implications for deformational style and flow in the crust, *Geophys. Res. Lett.*, *31*, L23601, doi:10.1029/2004GL021096.
- Percival, J. A., and R. N. Pysklywec (2007), Are Archean lithospheric keels inverted?, *Earth Planet. Sci. Lett.*, *254*(3–4), 393–403.
- Peselnik, L., A. Nicolas, and P. R. Stevenson (1974), Velocity anisotropy in a mantle peridotite from the Ivrea zone: Application to upper mantle anisotropy, *J. Geophys. Res.*, *79*(8), 1175–1182.
- Ramsay, J. G. (1975), The structure of the Chindamora batholith: 19th Annual Report of the Research Institute of African Geology, University of Leeds., 81 pp, Leeds, U. K.
- Savage, M. K. (1999), Seismic anisotropy and mantle deformation: What have we learned from shear wave splitting?, *Rev. Geophys.*, *37*, 65–106.
- Schmitz, M. D., et al. (2006), High-precision U-Pb geochronology in the Minnesota River Valley subprovince and its bearing on the Neoproterozoic to Paleoproterozoic evolution of the southern Superior Province, *Geol. Soc. Am. Bull.*, *118*, 82–93.

- Shapiro, N. M., et al. (2004), Lithospheric structure of the Canadian Shield inferred from inversion of surface-wave dispersion with thermodynamic a priori constraints, *Geol. Soc. London, Spec. Publ.*, 239(1), 175–194.
- Silver, P. G. (1996), Seismic anisotropy beneath the continents: Probing the depths of geology, *Annu. Rev. Earth Planet. Sci.*, 24, 385–432.
- Silver, P. G., and W. W. Chan (1991), Shear-wave splitting and subcontinental mantle deformation, *J. Geophys. Res.*, 96, 16,429–416,454.
- Silver, P. G., et al. (2004), Seismic anisotropy, mantle fabric, and the magmatic evolution of Precambrian southern Africa, *S. Afr. J. Geol.*, 107, 45–58.
- Simmons, G., and H. F. Wang (1971), *Single Crystal Elastic Constants and Calculated Aggregate Properties: A Handbook*, The MIT Press, Cambridge, Mass.
- Southwick, D. L. (2002), Geologic map of pre-Cretaceous bedrock in Southwest Minnesota, in *Geological Survey of Minnesota, University of Minnesota* (Editor).
- Southwick, D. L., and V. W. Chandler (1996), Block and shear-zone architecture of the Minnesota River Valley subprovince: Implications for late Archean accretionary tectonics, *Can. J. Earth Sci.*, 33, 831–847.
- Vinnik, L. P., et al. (1995), Recent deformations of the deep continental root beneath southern Africa, *Nature*, 375, 50–52.
- Waite, G. P., D. L. Schutt, and R. B. Smith (2005), Models of lithosphere and asthenosphere anisotropic structure of the Yellowstone hot spot from shear wave splitting, *J. Geophys. Res.*, 110, B11304, doi:10.1029/2004JB003501.
- Whitney, D. L., and B. W. Evans (2010), Abbreviations for names of rock-forming minerals, *Am. Mineral.*, 95(1), 185–187.
- Wüstefeld, A., G. Bokermann, C. Zaroli, and G. Barruol (2008), SplitLab: A shear-wave splitting environment in Matlab, *Comput. Geosci.*, 34(5), 515–528, doi:10.1016/j.cageo.2007.08.002.
- Yuan, H., and B. Romanowicz (2010), Lithospheric layering in the North American craton, *Nature*, 466(7310), 1063–1068.